Principles of Data Acquisition Systems

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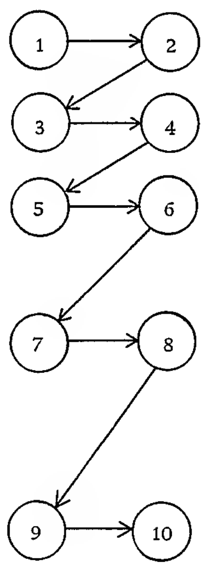
INTRODUCTION

Technological advancements in such fields as aerospace, biomedical and industry in general have created a need for timely, accurate and reliable measurement of data at its source for control and evaluation. Data acquisition systems perform both a checkout function, which includes manual or automatic programmed stimulus, and a control function, which can include feedback or adaptive stimulus by hardware. The classes of activities of a data acquisition system include the acquiring and display of data for such activities as rocket engine tests, wind tunnel operations, vehicle trials, environmental test chambers, electronic systems test, nuclear reactors, chemical process plants and medical research studies.

The following chart illustrates the progression of a typical data acquisition system in a testing environment beginning with a single measurement function for monitoring purposes and evolving into a real-time system under control of a digital computer:



FUNCTION	SYSTEM PROGRESSION
Monitoring a single measurement.	Single transducer with recorder
Increased testing requirements.	Multiple transducers with multiple recorders.
Quick-look requirements. Offline data analysis.	Many transducers with multiplexing, recording on analog tape, and display of critical values.
Online limit checking. Economics of system design.	Events recorder evaluators, analog-to-digital converters, digital-to-analog converters, digital tape and digital displays.
Increased system accuracy, flexibility and response for checkout and control	Real-time data analysis using online digital computer.

The basic purpose of a data acquisition system is to measure and record the operating characteristics of a particular item of equipment and/or process, and to check these operating characteristics in accordance with predetermined standards. The digital computer provides the means for evaluation of the acquired data and control of the acquisition process.

Systems that include computer control are characterized in general by large numbers of equipment and/or process-connected inputs. These may include analog transducer (sensor) inputs of different types, digital inputs, contact closures, and other digital data sources such as manual entry devices. System output may be special data outputs (both analog and digital) for control of displays, recorders and control mechanisms, as well as data recorded on magnetic tape, punched cards and in printed form. Functions performed by the computer include monitoring and controlling the sequence of various operating phases, evaluating input data against pre-established limits to detect malfunctions, calculating the derived parameters which measure the degree of success or failure of the operation, and formatting output display information to inform operators of the test status. Attachment of a digital computer to an online or real-time data acquisition system requires consideration of the following design criteria:

- System accuracy and resolution
- System reliability
- High-speed scanning and digitizing of analog inputs
- Individual and aggregate input/output data rates
- Provision for data to be edited and limit-checked in real time
- Provision for recording all and/or selected data
- Adequate core storage capacity
- Central processing unit design to provide overlapped input/output and computing
- A real-time clock and interval timers with interrupt capabilities

This manual is intended to describe the basic components, interfaces and configurations required for most data acquisition systems which employ online computers. It provides basic information for a preliminary understanding of the function and design of the individual components illustrated in the complete data acquisition system diagram shown in Figure 1.

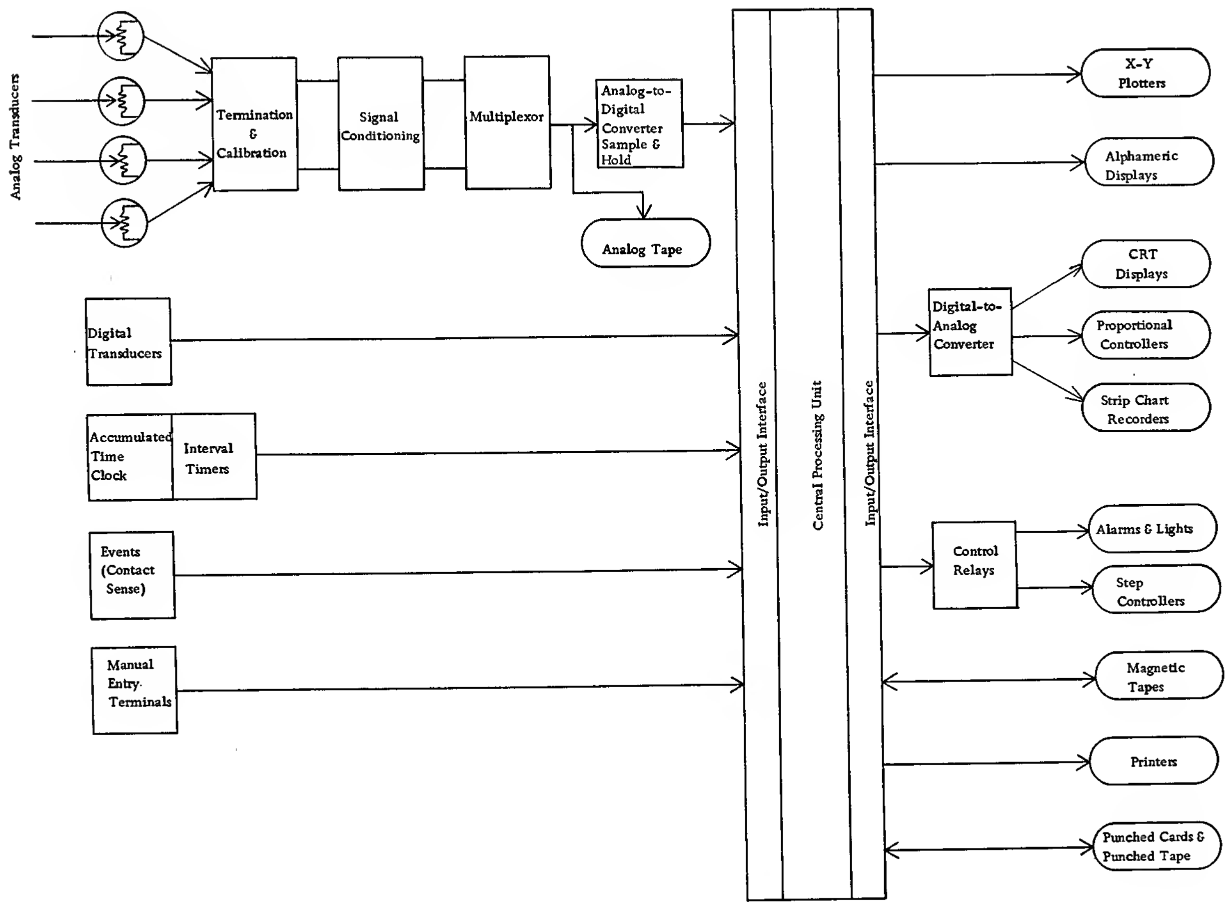


Figure 1. Data acquisition configuration diagram

DATA INPUT EQUIPMENT

ANALOG TRANSDUCERS

Data acquisition systems are used to measure physical quantities such as temperature, pressure, force, flow, acceleration, velocity and sound. The elements used to make these measurements are called sensors or transducers and their function is to convert mechanical or thermal energy to an electrical signal. Common types of analog transducers in use in data acquisition systems are strain gages, thermocouples, potentiometers, resistance thermometers and thermistors, and flowmeters. Less common types which may be encountered include photoelectric transducers, capacitive liquid-level gages, inductance displacement gages, hot-wire gas probes, piezoelectric gages and ionization vacuum gages. Transducers may be classified as having high-level or low-level output depending on whether the output is measured in volts or millivolts.

Some of the more common types of analog transducers that may be found in data acquisition system configurations are described in this section.

Strain Gages

Strain gages are resistive elements used to measure strain, pressure, or force. They are normally bonded to the object whose strain is to be measured — for example, the diaphragm of a pressure gage, or an elastic beam in a force-measuring load cell. Application of a force or pressure causes the object to stretch or shrink, thus causing a change in the length and cross section of the strain gage element, which correspondingly changes its electrical resistance.

Strain gage elements may be connected singly or in pairs in a bridge circuit as shown in Figure 2. The strain gage elements are arranged so that application of force or pressure causes a net unbalance of the bridge. Excitation voltage for the bridge may range from five to 24 volts, and the full-scale bridge output is of the order of 10 - 100 millivolts.

Strain gages require a power supply for excitation and usually require a zero or balance adjustment for initially balancing the bridge while no pressure or force is on the gage. Since one terminal of the power supply is normally connected to a common mode or system ground, the gage output is balanced so that the output terminals will have equal positive and negative voltages with respect to the ground point. Some consequences of this, including balanced amplifier inputs and common mode voltage rejection, will be discussed as a part of the signal-conditioning equipment.

The source resistance of standard wire strain gages is typically about 120 ohms. Some newer semiconductor strain gages have a much higher source impedance and a much higher output voltage for a given pressure or force applied.

Thermocouples

Thermocouples consist of a junction of two dissimilar metals in a unit to measure temperature. The electrical current generated by thermoelectric effect created at this junction varies with temperature and may be measured. Wires made of the thermocouple metals (protected from corrosion or oxidation by a metal or ceramic cover) are connected to form the measuring junction at one end and are attached to standard copper wires at a reference junction. The thermocouple generates a voltage which is dependent on the difference in temperature between the measuring junction and the reference junctions. The reference junctions, therefore, must either be maintained at a known, controlled temperature or must have their temperature independently measured to provide a reference for establishing the thermocouple output. Figure 3 illustrates a thermocouple system.

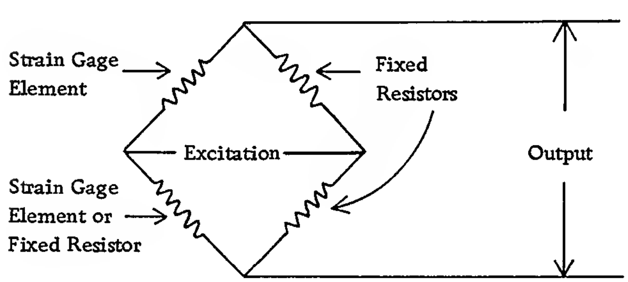


Figure 2. Strain gage bridge circuit diagram

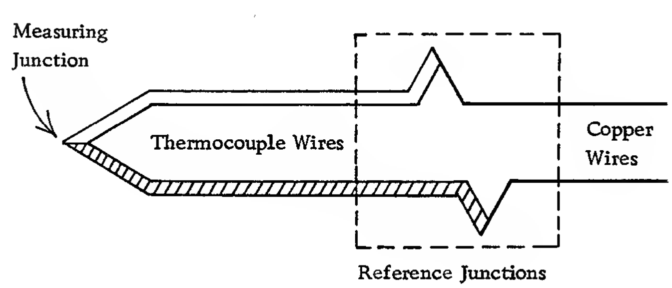


Figure 3. Thermocouple diagram

Common metal pairs used for thermocouple systems are copper-constantan, iron-constantan, and chromel-alumel. The type of thermocouple used depends on the temperature range to be measured. Each pair of metals has a well defined relationship of output versus temperature, which can be found in any standard engineering or physics handbook. This relationship is always nonlinear, which means that a calibration curve or table must be used to relate the thermocouple output to the measured temperature.

Thermocouple output voltages are always quite low and may range from fractions of a millivolt to several millivolts full scale. The internal resistance of a thermocouple is also low, typically of the order of 10 - 20 ohms. They require no power supply, and one of the copper signal leads may be connected to a common signal ground, giving an unbalanced or single-ended input to the signal-conditioning equipment.

Potentiometers

Potentiometer sensors are conventionally used to measure the displacement of a valve or other mechanical element in a system. They consist of a straight or coiled resistance wire with a sliding contact mechanically connected to the moving element. The sliding contact may, for example, be physically connected to the moving diaphragm or coiled pressure tube in a pressure gage. The potentiometer resistance wire is connected to a power supply as shown in Figure 4.

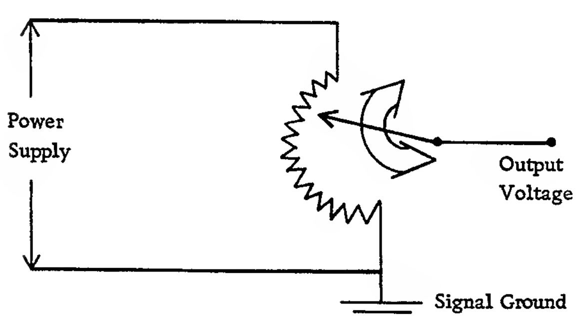


Figure 4. Potentiometer diagram

Since the full-scale output voltage is the full power supply voltage, the potentiometer output is limited only by the voltage and current rating of the resistance wire. The output signal is therefore high level, of the order of five or ten volts full scale. One side of the signal output circuit is common with the power supply and connected to signal ground, thus giving an unbalanced or single-ended output.

Resistance Thermometers and Thermistors

Resistance thermometers and thermistors are additional temperature-measuring devices which depend on a change of resistance of the sensor element to generate a signal which is a measure of the sensor temperature. Resistance thermometers have a resistance element made of a material such as platinum which has a high temperature coefficient of resistance and which maintains a stable resistance over a long period of time. A resistance thermometer requires a power supply and is normally connected in a bridge circuit similar to a strain gage. Resistance thermometer outputs are low level, in the order of a few millivolts, and are generally balanced with respect to signal ground. They are often used to measure very low temperatures, such as those of cryogenic rocket fuels, where thermocouples are not completely satisfactory.

Thermistors are semiconductor resistance elements made of iron oxide and other metallic oxides. They have a high negative temperature coefficient of resistance and a variation of resistance with temperature which is exponential rather than linear. They are more sensitive to small temperature changes than either thermocouples or resistance thermometers, but are less stable and less accurate. They are commonly used where very small temperature changes must be measured without a great deal of precision. They require a power supply and may be connected in circuits of either a balanced or unbalanced output. Output signals up to several hundred millivolts may be obtained for reasonably large temperature changes.

Analog Flowmeters

Analog flowmeters have an impeller or turbine-type rotor mounted inside the fluid channel whose flow must be measured. The rotor has magnetic vanes and a magnetic pickup outside the channel to generate an AC voltage with a frequency proportional to the flow rate in the channel. A frequency-to-DC converter is then used to provide an analog voltage which is a measure of the fluid flow rate. Standard commercial frequency-to-DC converters can handle flowmeter frequencies up to 5,000 cps and have full-scale output voltage of five volts.

In some applications the flowmeter frequency is measured by counting cycles directly for a measured time interval, and the count is entered into the data acquisition system in digital form (see "Digital Transducers").

Special Transducers

Other special transducers which may be used in data acquisition systems have characteristics dependent on the particular application. Transducers such as capacitive liquid level gages and inductance displacement gages require AC excitation sources and must have demodulators to convert the output signal to an analog voltage. Some piezoelectric sensors and other devices used in nuclear testing, such as scintillometers and proportional ionization counters have pulse outputs which require peak-holding circuits to hold the peak value of the pulse for input to the data acquisition system after the original pulse has decayed.

Most of these special transducers will have amplifiers, signal-conditioning and compensation circuits associated with them.

THE "FRONT END"

The term "front end" is commonly used to describe the component functions of a data acquisition system for acceptance of the signals from the analog transducers as input into the central processing unit. The functions of the front end may include any or all of the following:

- Termination and calibration
- Signal conditioning
- Analog multiplexors (high and low level)
- Sample-and-hold amplifiers
- Analog-to-digital converters

Termination and Calibration

All analog transducers require some form of termination equipment, if only a set of terminals to which to connect the transducer leads. Most transducer channels will also require calibration equipment which checks the accuracy and linearity of the signal-conditioning, multiplexing and conversion equipment required for getting the transducer reading into the computer. Calibration is required to correct for component and circuit changes caused by temperature variation and long-term aging.

Two types of calibration circuits are generally used. For voltage calibration the transducer is normally disconnected from the system, and precisely controlled voltages corresponding to those which would be received from the transducer are switched on to the transducer channel. A single voltage corresponding to the full-scale transducer output may be used for single-point calibration, or a number of voltage steps corresponding to, say, 25, 50, 75 and 100% of the full-scale output may be used for a more complete calibration.

For strain gages and other resistance-type transducers, a calibration method known as R-Cal is often used. In this method the transducer remains connected to the system. Its resistance element is shunted with one or more fixed, precision calibration resistors which change the overall circuit resistance in precisely the same way that the transducer resistance changes over its full range.

Actuation and sequencing of the calibration switches may be accomplished manually or under central processing unit control. Although calibration data is normally taken before and after a system run, intermediate calibrations may be made for lengthy runs. The raw calibration data is included as a part of the recorded data and is used in post-run data processing to correct the raw transducer data before conversion to engineering units and use in other processing routines.

Termination and calibration equipment for strain gages may include, in addition to the R-Cal system described, bridge completion resistors, a bridge balance or zeroing adjustment, and zero-offset capability. In some cases the strain gage power supplies may be included as part of the termination equipment.

Bridge completion resistors are fixed, precision resistors which are required to complete the strain gage bridge circuit, if it is not already completed at the transducer. The bridge balance or zeroing adjustment is necessary to compensate for small changes in the strain gage element or bridge resistors caused by temperature or aging effects. It allows the strain gage signal output to be balanced at exactly zero net volts with no pressure or force on the gage.

The zero-offset capability may be provided by the zeroing adjustment or it may be a separate control. This capability allows the output of the strain gage circuit to be set at zero volts with some pressure or force other than zero on the gage. Thus, if a pressure gage which normally reads 0 to 5,000 psi (pounds per square inch) is to be used in a test where the measured pressure ranges only from 3,000 to 5,000 psi, it is desirable to set the zero voltage output point at 3,000 psi and to increase the amplification so that full-scale output is reached at 5,000 psi. The gage output then ranges from zero to full scale over the pressure range 3,000 to 5,000 psi. Zero offset may be achieved by deliberately unbalancing the gage output or by adding a separate offset voltage equal to the normal gage output at the desired zero point. Zero-offset capability may be required for thermocouples and other analog transducers as well as strain gages.

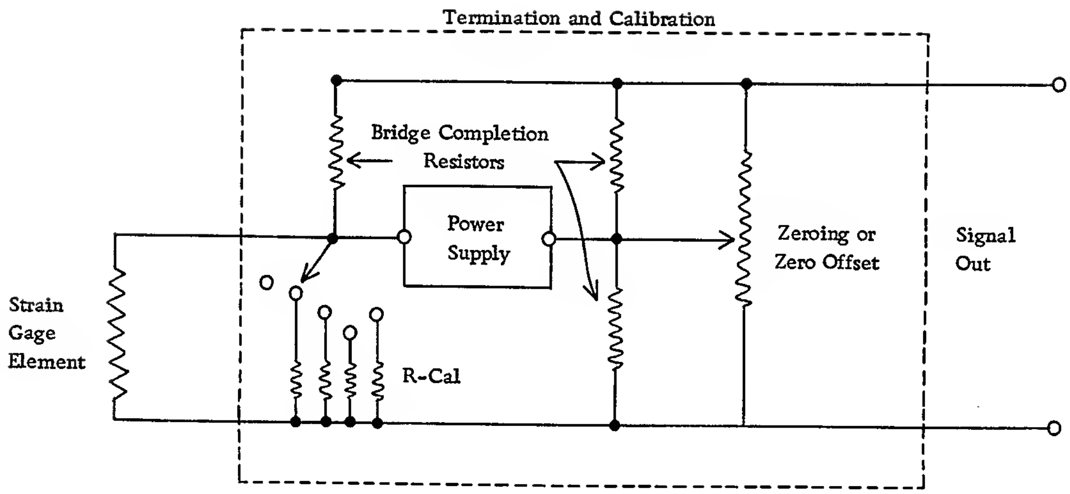


Figure 5. Strain gage termination and calibration diagram

A complete strain gage termination and calibration system is shown in the diagram in Figure 5.

Termination equipment for thermocouples includes reference junctions and a reference junction temperature transducer. A resistance thermometer, for example, may be used to measure reference junction temperature. Readings of thermocouple voltage, resistance thermometer output voltage, and the resistance thermometer power supply voltage are all entered into the central processing unit, where the temperature measured by the thermocouple is calculated from these readings. Calibration of thermocouple channels is generally accomplished by the voltage calibration technique.

Signal Conditioning

Signal-conditioning equipment includes the amplifiers and filters necessary to raise the transducer signals to the levels required for switching by the multiplexor, and to filter out unnecessary frequency components or noise from these signals.

Amplifiers may have either single-ended or balanced inputs. For single-ended inputs, one of two input lines from a transducer is connected to signal ground and the other is either positive or negative with respect to the ground at any instant. In the case of a balanced input, the two transducer lines have equal but opposite voltages with respect to ground at any instant. Balanced inputs are required for strain gages and other bridge-connected transducers. The voltage which is amplified in a balanced input amplifier is the difference between the voltages on the two lines. This is the normal signal voltage produced by the transducer system.

In most data acquisition systems there are additional voltages on the transducer lines caused by electromagnetic pickup and the impossibility of providing zero potential remote ground points. These voltages have equal polarity and equal magnitudes on the two lines from a single transducer and therefore tend to cancel out in a balanced input amplifier. They are called "common mode" voltages. The diagram in Figure 6 illustrates how common mode voltages can arise. Any slight unbalance in the amplifier causes some of the common mode voltage to appear as signal voltage and therefore degrade the accuracy of the system. The ability of the balanced-input amplifier to discriminate between common mode and signal voltage is called the common mode rejection ratio. A common mode rejection ratio of 1,000,000 to 1 is often required in data acquisition systems. This means that a common mode voltage of ten volts will produce an error of only ten microvolts in the transducer reading. The common mode rejection ratio is usually a function of the amount of resistance unbalance in the input circuit to the amplifier as well as the frequency of the input signal.

Amplifiers for low-level transducers commonly have a gain which is adjustable in steps up to several thousand. High-level transducers may require unity gain amplifiers for impedance matching.

Amplifiers used with transducers such as capacitance and inductance displacement gages, which

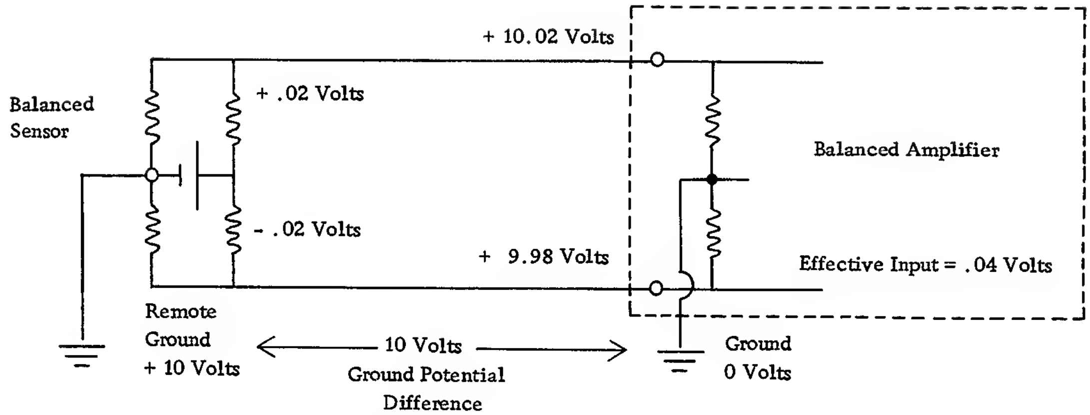


Figure 6. Common mode voltage diagram

use AC excitation, usually have several stages of AC amplification with a demodulator or an AC-to-DC converter to provide a DC analog output.

Filters are used in most transducer channels to limit the frequency bandpass of the channel. They cut down noise and unwanted extraneous pickup. Frequencies in the transducer signal which are an appreciable fraction of the channel sampling frequency will tend to produce errors in the multiplexor output. For this reason, the channel filter cutoff points are normally set at some frequency well below the channel sampling rate.

Multiplexor

The multiplexor is basically a set of fast switches or gates which sample each of the input transducer channels in a fixed or random order and allow them to time-share a single channel to the analog-to-digital converter. Important characteristics of multiplexors are the sampling or switching rate, input signal voltage levels, number of channels, sequencing method, noise level and presence of crosstalk.

Multiplexors using mechanical (relay) switches can achieve sampling rates up to a few hundred samples per second. They may be adequate for many activities where transducer signals change relatively slowly. Mechanical multiplexors have the advantages that they are inexpensive and reliable, and can be used to sample low-level signals without prior amplification. Their speeds are not adequate, however, in dynamic, rapidly varying applications such as rocket and jet engine checkout.

Higher sampling rates are obtained by using solid-state (transistor) switches. At the present state-of-the-art, precision multiplexors have maximum rates of 50,000 samples per second. The maximum sampling rate of the multiplexor in a complete system is normally limited by the conversion time of the analog-to-digital converter, since it does no good to sample data faster than it can be converted. Thus, to achieve higher sampling rates, faster analog-to-digital converters are required. Solid-state multiplexors have been built in the past to handle high-level signals of five to ten volts full scale. Because of the expense in large systems of providing a separate amplifier for each low-level input channel, high-speed, low-level multiplexors have been developed. These use low-level switching circuits which allow at least a part of the required amplification to be placed behind the multiplexor where a single amplifier will suffice for all channels. By suitable combinations of preamplification and postamplification they can handle input signals of a few millivolts full scale.

Multiplexors may be designed to be modularly expandable to handle some small number of channels up to a maximum of several hundred. The total number of channels possible depends on the capacity of the sequencing system and the switching circuit speeds. Two types of sequencing systems are in general use. The first uses a stepping switch having a number of positions equal to the total number of samples taken in one complete sequence for stepping sequentially through all of the channels. A patchboard is generally used between the sequencer and the multiplexor so that any multiplexor channel can be tied to any position or positions of the sequencer. This allows the channels to be sequenced in any order. It also allows single channels to be "cross-strapped", or tied to a number of positions of the sequencer, so that those channels may be sampled more frequently than others.

The second type of sequencing system employed by multiplexors in modern, large-scale systems generally uses an addressing scheme for channel sequencing. An address decoder is incorporated with the multiplexor to enable it to decode a binary input address and open the channel gate corresponding to the address. Because any channel may be addressed at any time, this feature is called random sequencing. In computer-controlled systems the multiplexor may be addressed by the central processing unit. The sequence of channels to be addressed is contained in a table of addresses in its core storage. The total number of channels which may be addressed (the channel capacity of the multiplexor) is dependent on the number of bits in the address word.

Because noise generated in the signal channel by the multiplexor directly affects the system accuracy, such noise must be kept as low as possible. In addition, the separate channels must be sufficiently shielded so that coupling or crosstalk of signals in one channel into a different channel will be absolutely minimized. Multiplexor noise and crosstalk specifications must be compatible with the required overall system accuracy.

Sample-and-Hold Amplifier

To allow overlap of multiplexing and conversion and to prevent system errors which may result from changes in the input signal during the conversion cycle, a sample-and-hold amplifier is normally used between the multiplexor and the analog-to-digital converter. This amplifier samples each analog input signal from the multiplexor for a very short period of time (generally about one microsecond), then holds a constant output value equal to the value of the input signal for the conversion process. The sampling time of the sample-and-hold amplifier is called its aperture time.

Analog-to-Digital Converter

The analog-to-digital converter receives the high-level analog signals from the multiplexor and converts them to a digital format acceptable by the central processing unit. Important characteristics of analog-to-digital converters are the conversion rate, resolution, output format, accuracy, stability and linearity. The maximum conversion rates of present high-resolution analog-to-digital converters range up to 50,000 conversions per second. Lower-resolution units may operate as high as 500,000 conversions per second.

Resolution is used here to mean the least count present in the digital output. The highest-resolution converters now available have resolutions of approximately one part in 16,000. This is near the practical limit of meaningful resolution achievable, since any greater resolution is masked by multiplexor and amplifier noise. Medium-resolution converters are commonly used in systems where maximum accuracy is not required. These converters have resolutions of the order of one part in 4,000. Commonly encountered lower-resolution converters have a resolution of one part in 1,000.

Converter output formats are either binary or binary coded decimal (BCD). Binary analog-to-digital converters have outputs in 14, 12 or 10 bits (plus a sign bit) according to the high, medium and low resolutions described above. BCD converters are obtainable with three or four BCD characters output, providing a resolution of one part in 1,000 or one part in 10,000. BCD output is in standard four-bit (8, 4, 2, 1) numeric characters. Both binary and BCD converters normally provide a parity indication. In binary converters parity is assigned on a per-word basis, whereas for BCD converters it is assigned on a per-character basis.

Many presently installed data acquisition systems which do not have online central processing units use BCD analog-to-digital converters because of the ease with which this format can be placed on magnetic tape, and because simple decimal displays can be built to handle this format. With the introduction of high-speed binary computers into data acquisition systems it has become more economical to use analog-to-digital converters with binary output. However, where computers are introduced into existing systems, it is often necessary for the central processing unit to perform BCD-to-binary conversions on the input data which is to be used in high-speed computation.

The simplest and least expensive analog-to-digital converter available today is the mechanical rotating shaft converter, which is limited in use by its low conversion speeds of two to ten conversions per second.

Another method in use today is the ramp or sawtooth analog-to-digital converter in the intermediate-speed range, which converts data at the rate of 100 to 1,000 samples per second. The operation of a ramp-type converter (Figure 7) is initiated by means of a gate pulse applied to the ramp generator. The ramp generator produces a triangular waveshape which does two things. First, as the rising waveshape becomes equal to or greater than the zero reference signal applied to comparator number 1, a pulse is produced which sets a trigger in the control unit; second, when the waveshape becomes equal to or greater than the analog voltage input applied to comparator number 2, a pulse is generated to reset the trigger in the control unit. The result of this operation is a control unit-produced pulse of a duration proportional to the amplitude of the input

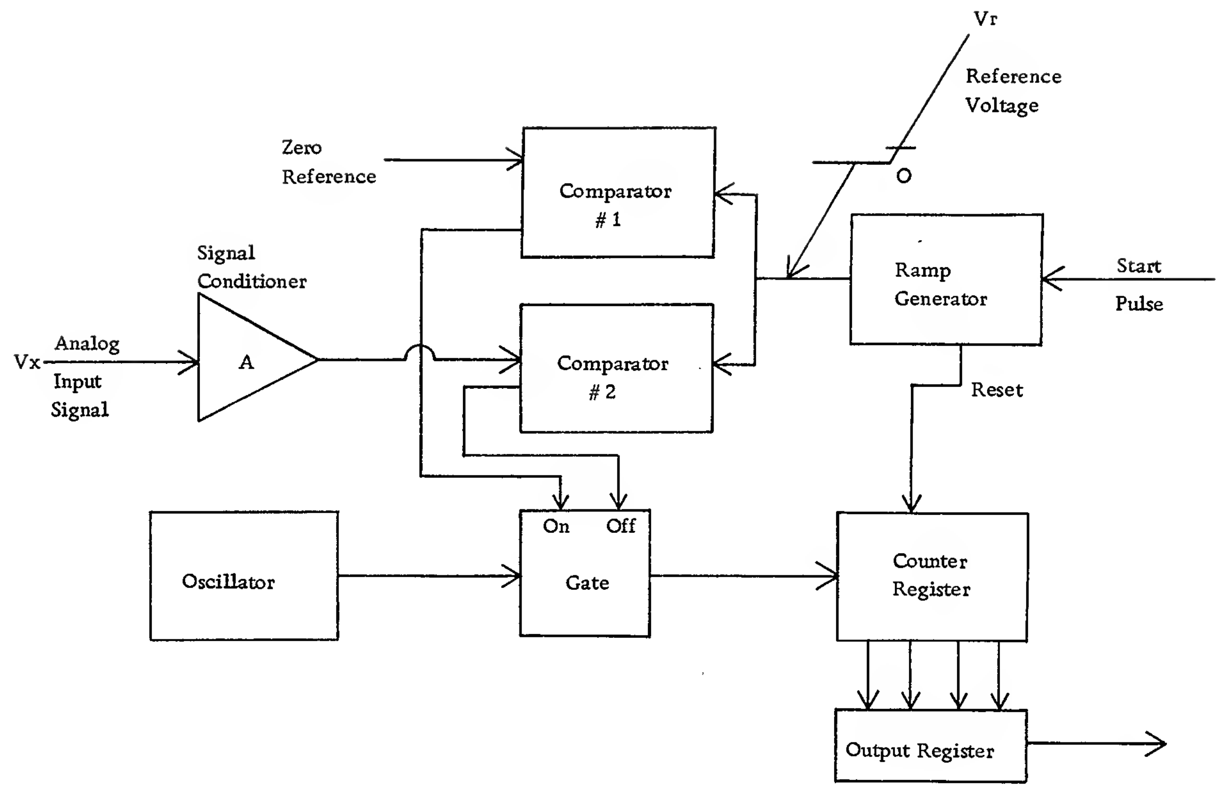


Figure 7. Ramp or sawtooth analog-to-digital converter diagram

signal. This control pulse then gates an oscillator which feeds a digital counter. The output of this counter is a digital representation proportional to the analog input signal.

When the ramp voltage reaches its maximum value, the trailing edge of the ramp signal is used to generate a reset pulse which gates the counter reading to an output register and resets the counter to zero.

The operation of a staircase converter is similar to that of the ramp converter except that the staircase reference voltage is discrete rather than continuous (see Figure 8). The operation begins with a start pulse to a gate that controls an oscillator which in turn feeds pulses to a digital counter containing an initial value of zero. The counter then feeds a digital-to-analog converter containing a summing network which encodes the counter output into a voltage output called a staircase. This staircase voltage increases discretely as the counter increases. The output of the digital-to-analog converter feeds a comparator until the reference value is equal to

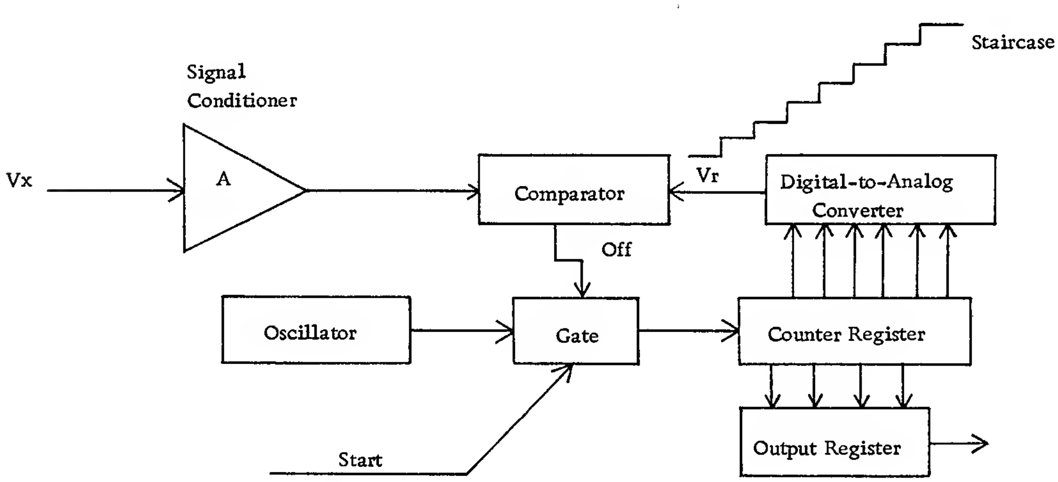


Figure 8. Staircase analog-to-digital converter diagram

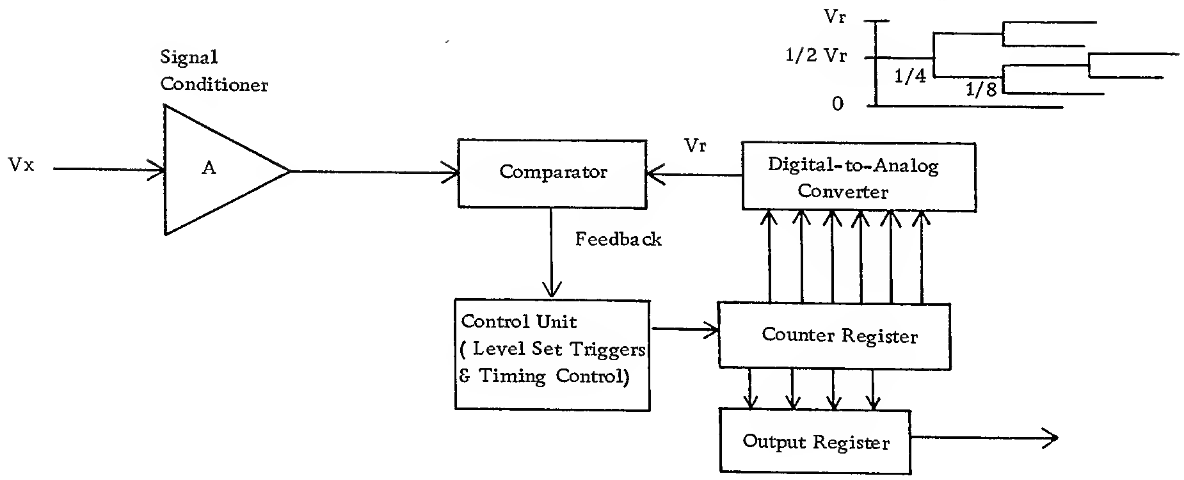


Figure 9. Successive approximation analog-to-digital converter diagram

the input, at which time the comparator generates a stop pulse to the gate, turning off the oscillator. The contents of the digital register are now proportional to the input analog signal. The stop pulse generated by the comparator also steps the counter results to an output register and resets the counter to zero.

The analog-to-digital converters in wide application in high-speed data acquisition systems are the successive approximation type which operate at conversion speeds up to 100,000 samples per second with a resolution of 14 binary bits and with an accuracy of .01%. In the operation of a successive approximation converter (Figure 9), the oscillator and gate shown in the staircase converter are replaced by a control unit and the operation involves a feedback reference voltage.

The operation begins with a start pulse to the control unit, which contains a timing control unit and level setting triggers. The level triggers are set in such a manner that their output to the digital-to-analog converter results in a value of voltage equal to one-half the maximum permissible value of the input analog signal. The comparator then makes a decision as to whether the input analog signal is greater or less than the digital-to-analog converter reference voltage. The state of the level setting triggers on the control unit is then modified accordingly. For example, if the reference signal is too large, it is discarded and a quarter-scale reference voltage is tried. The process then continues until the reference voltage in the comparator is equal to the input analog signal, at which time the level setting triggers reflect the amplitude of the input signal. The results are then stepped to an output register. Since these approximations are performed serially, the analog-to-digital conversion process is generally the limiting factor in the overall data acquisition rate.

The accuracy, stability and linearity of the analog-to-digital converter contribute to the overall accuracy specification for the analog system discussed in the following section.

Analog System Accuracy

The overall analog system accuracy is defined as the difference between the digital output representation of an analog voltage and the actual value of the input voltage to the signal-conditioning equipment, expressed as a ratio of the input voltage. Accuracy is a function of the errors contributed by the signal-conditioning amplifiers, the multiplexor and the analog-to-digital converter.

Three types of errors are encountered: random errors, linearity errors, and stability errors. Random errors are those which are due primarily to random noise in the equipment. Linearity errors are the deviations from a straight line (linear variation) in the output of a unit when the input is varied linearly. Stability errors are the drifts of a unit from a fixed output when the input is held fixed for a given length of time. Because these errors combine in various ways, the overall accuracy of the system is not a constant but is a function of the input signal amplitude and of the length of time since the last system calibration. A complete specification of system accuracy, therefore, requires a specification of the random inaccuracies, the system linearity and the system stability.

In addition, there are other factors which may influence accuracy — for example, temperature variation and electromagnetic environment.

DIGITAL TRANSDUCERS

The most common types of transducers which provide direct digital outputs are those which measure frequency and period. The frequency of a recurring signal can be measured by counting axis crossings of the signal over a fixed interval of time. Similarly, the period of an alternating signal can be measured by counting pulses from a stable clock pulse generator between axis crossings of the signal. These techniques can also be used to count the number of discrete events occurring in a given time interval and to measure the time between two events.

A frequency counter is often used to give a digital readout of flow rate from a flowmeter, as mentioned previously. The period-measuring technique is often used simultaneously to give, at the time of data readout, the time elapsed since the last axis crossing of the flowmeter signal. This is accomplished by having each axis crossing of the flowmeter signal reset the period counter to zero. The use of both frequency and period measurement techniques can give a very accurate measurement of flow rate.

Frequency or event counters are also often used in nuclear reactor testing in conjunction with Geiger tubes or neutron detectors. The number of particles detected in a fixed interval of time is a measure of the power level of the reactor.

In all of these applications, the count is accumulated in a register which may be read and reset at the proper time.

Other types of transducers which have direct digital readouts are those in which a mechanical displacement or rotation is coded by means of brushes and contact bars, or other mechanical switches, to provide a digital representation. Included in this category are shaft position encoders as used on radar and tracking cameras, and liquid-level sensors in which a magnetic float picks various switches as the level changes. The switches are generally arranged to give a Gray code representation (in which there is only one bit change between adjacent words) of the measurement. The code is sampled and read out in parallel when called for by the data acquisition system.

Contact Sense (Events)

In almost all data acquisition systems there is a requirement to monitor or record the status of devices such as switches or valves, by a binary representation to indicate on or off, open or closed. Each device is usually provided with a set of contacts which put a constant voltage on a line to the data acquisition system when the device is actuated. The presence or absence of voltage on the line is read as a 1 or 0 (bit or no-bit) by the system. The lines are arranged in groups having the same number of bit positions as the system input word, and all lines in each group are read simultaneously for input to the central processing unit as a standard data word.

Additional circuits may be added to some of the lines to change slightly the way in which they operate. For example, certain of the lines may be connected to latching switches which will close when even a momentary voltage pulse is received on the line and they hold that state until reset. Other lines may be connected to switches which will not change their state until the voltage changes on the line have been sustained for a given length of time. This type of operation is useful for suppressing the effects of contact bounce and relay chatter.

Another very useful procedure of contact sense usage employs special logic to generate a computer interrupt when one or more of the input lines change state. The computer may then read in and record the status of all lines and correlate the status change with elapsed time. This mode of operation may provide a closer time correlation of line events and eliminate the need for repetitive sampling and recording of all lines regardless of any actual status change.

Accumulated Time Clock

An accumulated time clock is used to provide a continuous measurement of elapsed time. The clock is either set to zero or GMT at the beginning of the procedure, and time data from the clock is sampled with every complete scan of the analog and digital data. Timing signals from the clock may also be used to control the data-sampling rates of the data acquisition system. Interval timers associated with the clock may be used to initiate periodic central processing unit interrupts to time such actions as the updating of displays and sequencing of test conditions.

The accumulated time clock comprises a highly stable oscillator and a counter. The time resolution required is normally about one millisecond, so the oscillator must have a frequency of at least one kc. The counter should be able to accumulate a time count at least as long as the expected duration of each data acquisition cycle. The accumulated time may be stored in external counter registers and read into the computer storage on demand, or the accumulated time may be retained in specific locations in the computer storage and updated by the clock oscillator.

Manual Entry Data

There is almost always a requirement in data acquisition systems for the entry of fixed data. This data may include such identification information as the date and time of day, configuration identification data, the number of items online, and the number of the facility on which the procedure is being run. The fixed data may also include measurements such as the barometric pressure, humidity and ambient temperature.

Data is normally entered manually by positioning decade switches or thumb wheels. A computer entry switch may be provided to transfer the data to core storage. Alternatively, the data can be entered on an input typewriter. The data may then be recorded only once as initial information or repeatedly entered at the heading of each tape record or data scan.

Channel Addressing

Selection and sequencing of input data channels may be performed in computer-controlled data acquisition systems by channel addressing. Similarly, the output of data to display units and other output devices is also often performed by channel addressing which selects the particular output device required.

Channel addressing may be done by sending out system address words on a single set of address lines to all addressable channels or devices. The address words must contain sufficient bits to be able to address all channels and devices uniquely. Address words are generally stored in a table or tables in the central processing unit storage for output sequentially as needed.

Address decoders are provided at all separately located devices to recognize pertinent addresses and select corresponding channels.

An important part of the design of a data acquisition system is the selection of address word formats. Separate devices having groups of data channels (such as analog multiplexors and digital data channels) may have their addresses contained in different parts of the output address word. These devices may then contain smaller decoders which examine only those bit positions of the output address word that contain their addresses. Where excess address-word bits are available and only a few single-channel devices are to be addressed, flag bits may be used to select the device. Very simple decoders may then be used to detect only the presence of a bit in the position corresponding to the device selected.

The technique of random addressing of channels and devices under computer control allows great flexibility in the operation of a data acquisition system. Channel sequencing and channel sampling frequency are under stored-program control, and data formats, channels and sampling frequencies may be dynamically changed by updating or changing the stored address list. For example, initial parameters may be sampled more frequently during transient phases of a data acquisition program or in response to detection of out-of-limit conditions.

TELEMETRY SYSTEMS

The science of telemetry may be defined as the ability to measure from afar. A basic telemetry system consists of a radio signal transmitted from some remote point and containing many channels of information picked up by an antenna and a receiver subsystem. The receiving subsystem decodes the radio signal into specific channels of information for analog recording on magnetic tape or feeds signal-conditioning and decommutation equipment for computer processing and digital recording.

There are four major telemetry systems generally used today in data acquisition systems:

- FM — Frequency Modulation
- PAM — Pulse Amplitude Modulation
- PDM — Pulse Duration Modulation
- PCM — Pulse Code Modulation

Many of the systems used conform to standards generated by the Inter-Range Instrumentation Group (IRIG). An IRIG standard that is common to all telemetry systems is the r-f (radio-frequency) carrier frequency band 216 mc (megacycles) to 260 mc. Other IRIG standard r-f carriers are 1,435 to 1,535 mc and 2,200 to 2,300 mc.

In telemetry systems the objective is to enable the r-f carrier to carry more than one signal. For the r-f carrier to handle more than one channel of information, it is modulated by a group of subcarriers, each of a different frequency. The principle of showing one band of frequencies to represent one channel of information, and another band of frequencies to represent another channel of information, is called frequency-division multiplexing and is the basis for FM telemetry systems.

In PAM and PDM telemetry systems each of the individual subcarriers is modulated by a time-division multiplex scheme (commutation) to increase the number of individual data channels available. Time-division multiplexing essentially means that beginning with a prearranged signal, one unit of time represents one channel of information and the next unit of time represents another channel of information.

Frequency Modulation (FM)

An example of frequency-division multiplexing is FM/FM telemetry systems, where up to 18 different subcarrier frequencies can be applied to modulate

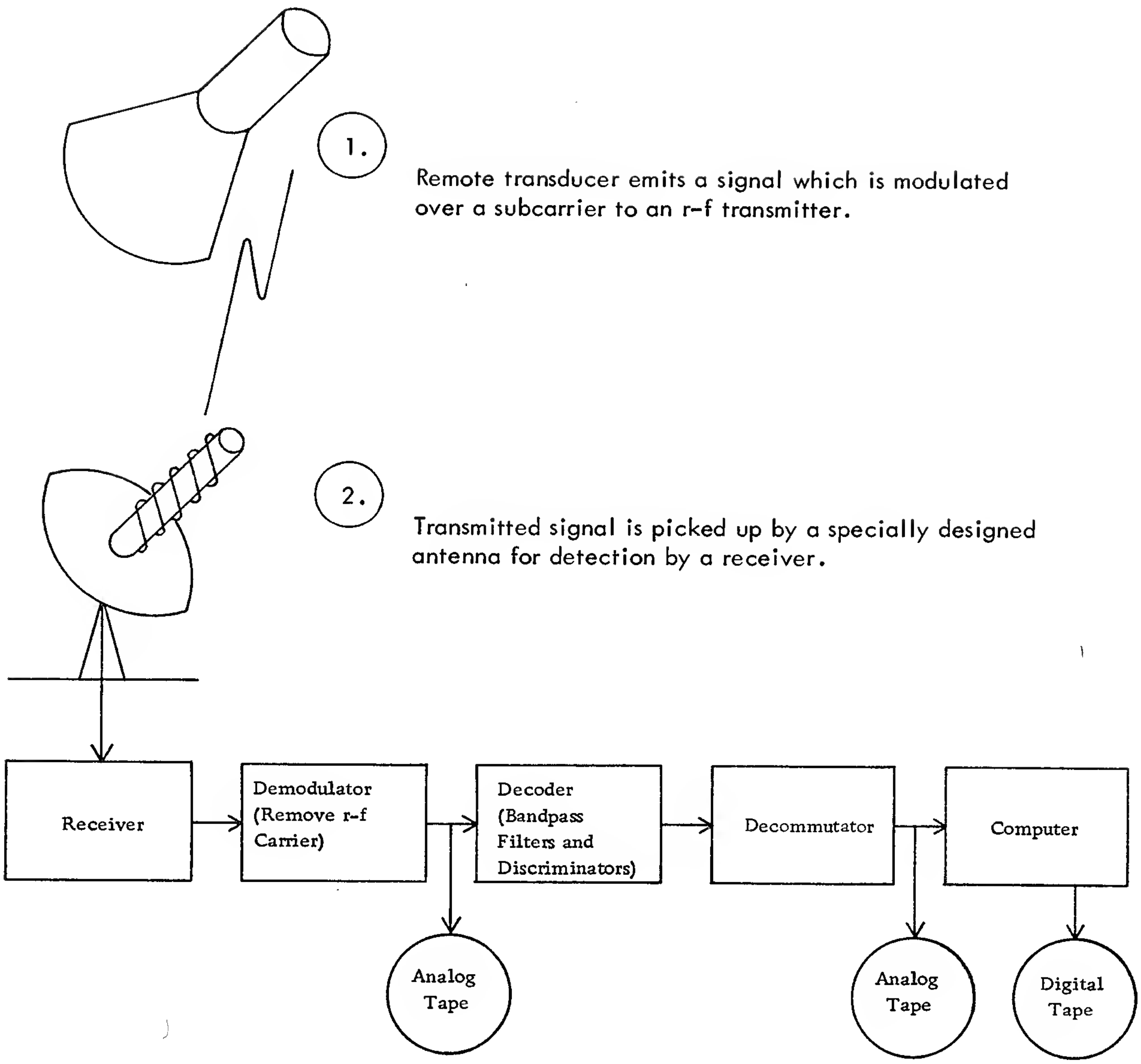


Figure 10. Basic telemetry system

the r-f carrier. These subcarriers in turn may be frequency-modulated by a transducer which provides a varying output. The output of the subcarrier oscillator then frequency-modulates a high-frequency r-f transmitter, the output of which is radiated by a specially designed antenna.

In FM/FM it is possible to use all 18 subcarrier oscillator channels (see Figure 15) to monitor 18 variables (transducers). However, if all 18 channels are in use, it is difficult to avoid crosstalk of the channels. Crosstalk results from harmonics of the lower-frequency oscillators mixing with the primary frequencies of the higher-frequency subcarrier oscillators. Another way of defining crosstalk is to state that information on each channel overlaps.

Figure 11 depicts an FM/FM multichannel system using multiple transducer outputs to modulate subcarrier oscillators and one transmitter. The outputs of the subcarrier oscillators (which generally contain linear mixing networks to eliminate crosstalk) mix together at the input to the FM transmitter. The output of each subcarrier oscillator, being different in frequency, independently modulates the transmitter, thus resulting in a mixing of the subcarrier oscillator frequencies to produce one complex composite signal. This technique of frequency-modulated subcarrier oscillators frequency-modulating a transmitter is the FM/FM system.

A limiting factor of frequency-division multiplexing is the single data channel (transducer output) to each subcarrier oscillator.

Time-division multiplexing utilizes transmissions of numerous transducer signals on a single carrier. This is accomplished by sampling the transducer

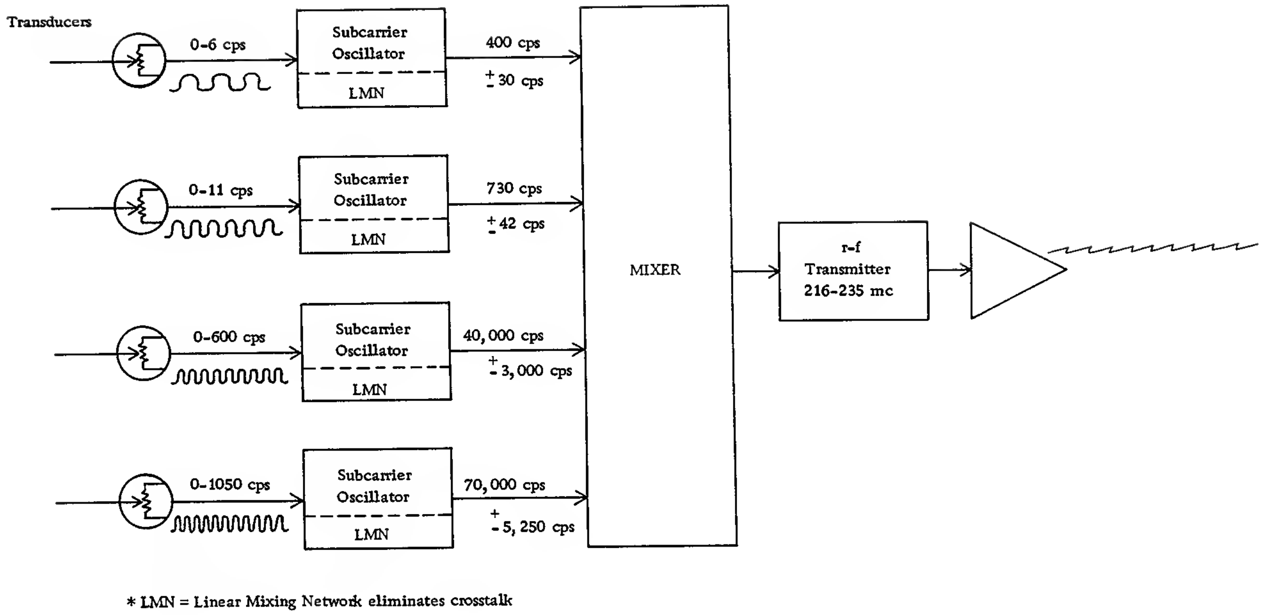


Figure 11. FM system

signals in succession by a sampling or switching device usually called a commutator. In this technique a unit of time represents a channel of information. PAM, PDM, and PCM are examples of telemetry systems that utilize time-division multiplexing.

Pulse Amplitude Modulation (PAM)

In this type of telemetry system, constantly varying transducer outputs are sampled and fed to a subcarrier oscillator as a series of pulses of constant width and position but of varying amplitude. The sample rate used in PAM is a function of the accuracy of the sampled signal. In a PAM telemetry system one complete revolution of the commutation switch is called a frame. The number of switch contacts in turn determines the number of samples per frame. The number of frames completed in one second is called the frame rate, and the number of samples per frame multiplied by the frame rate is the commutation rate. As the commutation rates increase, so does the number of information channels per second. This in turn requires a wider bandwidth, which is available by use of a higher subcarrier oscillator channel.

To ensure that the beginning of each frame is accurately known, a synchronizing or master pulse is used. This is referenced by the receiving station to identify the output of each specific transducer.

The technique of PAM information frequency-modulating a subcarrier oscillator which in turn

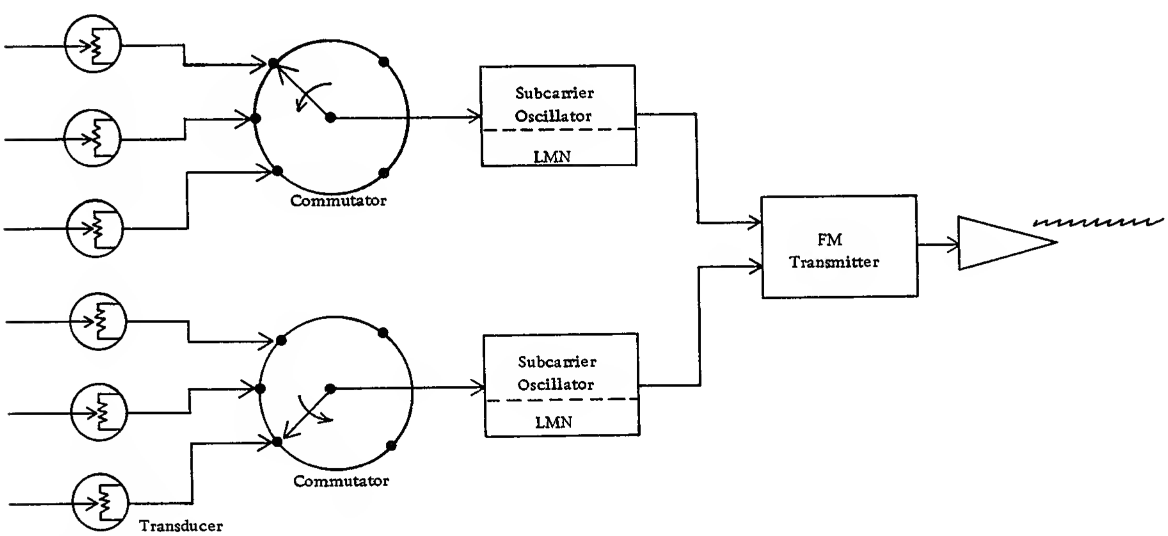


Figure 12. PAM-FM-FM system

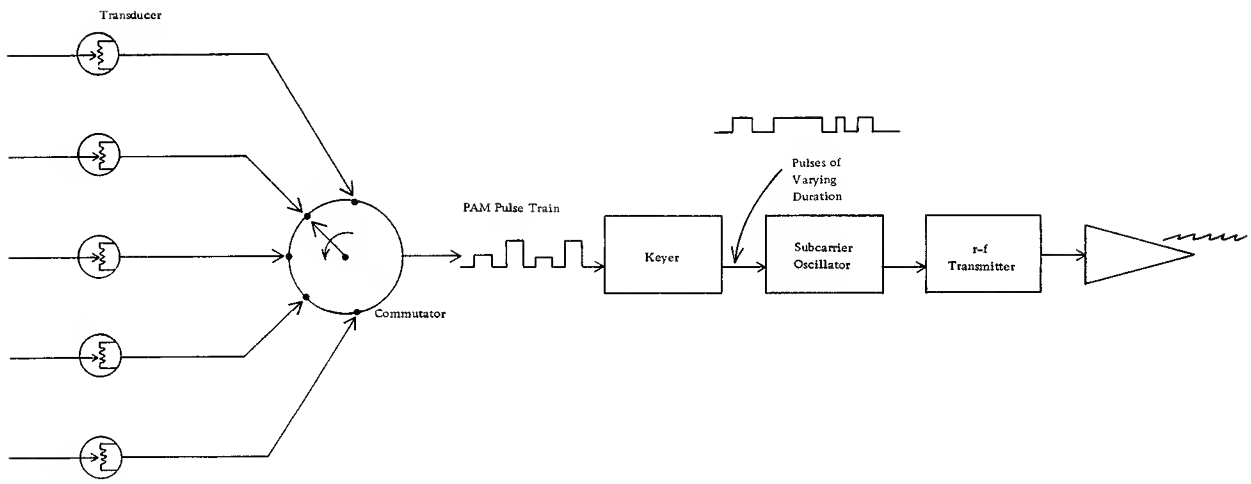


Figure 13. PDM-FM-FM system

frequency-modulates a transmitter is known as a PAM-FM-FM system. If only a few transducers are used in a system and it is possible to eliminate the subcarrier oscillator, thereby having the transducers directly modulate the transmitter, the system is known as PAM-FM.

Pulse Duration Modulation (PDM)

The components from the transducers to the commutator switch in a PDM telemetry system are identical with those of a PAM system. However, at this point the signal is applied to a keyer or pulse-width modulator. The function of the keyer is to convert varying-amplitude pulses into constant-amplitude pulses having variable widths. The output of the keyer is then applied to a subcarrier oscillator. While the frame rate and commutation rate are determined in the same manner as PAM, the commutation rate is always the same (900 samples per second). IRIG standards have been set up that determine the combinations of samples per frame and frame rate to equal 900:

Sample/Frame	30	45	60	90
Frames/Second	30	20	15	10
Frame Rate	900	900	900	900

Synchronization is obtained in a PDM system by the absence of two successive pulses. If the output of the keyer frequency-modulates a subcarrier oscillator to frequency-modulate a transmitter, this is then a PDM-FM-FM telemetry system.

Pulse Code Modulation (PCM)

Pulse code modulation is becoming one of the most important and significant of telemetry systems in use today, because it is based solely on digital techniques which greatly simplifies the ground station synchronization and signal-conditioning problems. PCM features high transmission accuracy (since the signal is either on or off) and has good signal-to-noise ratio if the signal is above the receiver threshold. Another advantage of PCM is that it is prone neither to wow and flutter error nor to errors caused by subcarrier oscillators, bandpass filters or discriminators.

A PCM system is similar to a PAM system from transducer to commutator. At that point, however, the various signal voltages are applied to a converter or coder which encodes the voltage reading to an equivalent binary representation of the amplitude of each input pulse. The pulses are then fed to a transmitter.

In determining which type of multiplexing system to use, such factors as component weight and space availability must be considered. From a reliability standpoint, frequency-division multiplexing utilizes parallel-type circuits, so that failure of an individual channel will not stop transmissions from the other channels. Time-division multiplexing, on the other hand, uses series-type circuits, so a failure in one (series-connected) unit may cause the failure of a complete system.

Frequency-division multiplexing systems can handle higher-frequency information because of continuous monitoring of the data channels. Time-division multiplexing, however, requires less bandwidth for the same number of information channels, since several transducers may be used to modulate a single subcarrier.

A particular advantage of PDM over PAM systems is that generally it is more difficult to distort data measured in time than to distort data measured in amplitude magnitudes, since the latter are very susceptible to noise inputs.

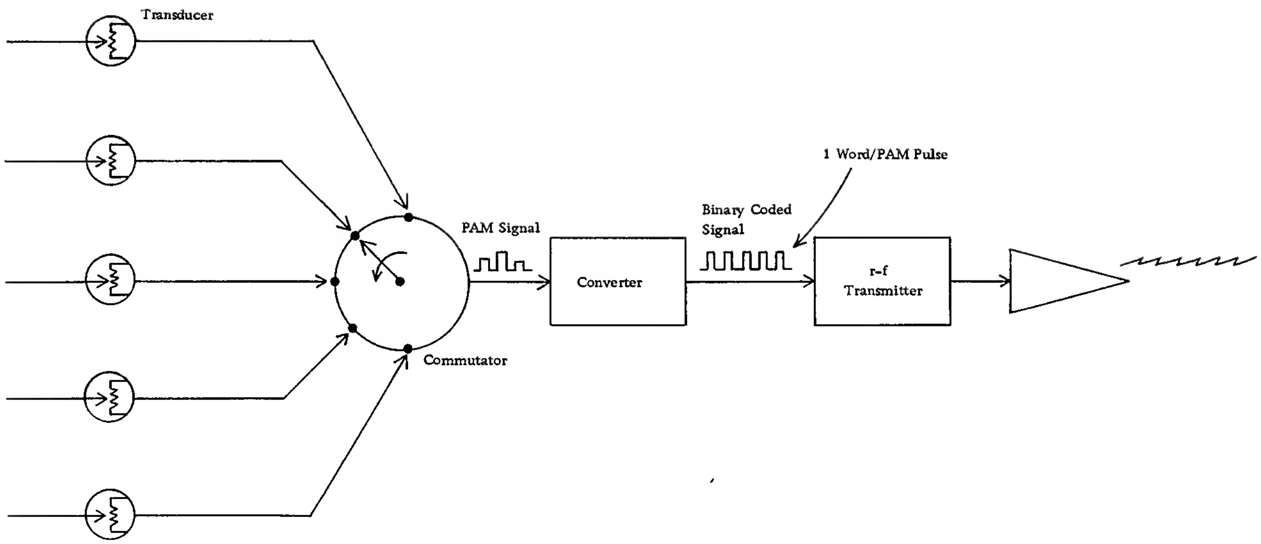


Figure 14. Basic PCM telemetry system

THE TELEMETRY FRONT END

At ground stations where telemetry data is to be recovered and recorded, the usual components are a receiving antenna, a preamplifier to increase signal strength, an FM receiver, a demodulator (to remove the r-f signal), and a decoder network which includes bandpass filters and discriminators. The output of these components is then a reproduction of the original composite signal consisting of the mixed subcarrier oscillator frequencies.

A spectrum display unit may also be used in ground station operations to provide visual aid in monitoring the frequency spectrum of the I-F portion of the FM receiver. The spectrum display unit visually shows any possible forms of signal interference on the screen of a cathode ray tube, thus permitting monitoring any or all of the subcarrier channels in use.

A bandpass filter is used to separate the individual subcarrier frequencies that make up the composite signals. A bandpass filter allows only a specific band of frequencies to pass. The bandpass filter output is then applied to an FM discriminator which converts the variations of subcarrier frequency back to the original analog signal coming initially from the transducer.

The signal output of these components can then be stored on analog tape or converted to a digital format for direct entry into a computer.

Band	Center Frequency (cps)	Max. Deviation (%)	Frequency Response* (cps)
1	400	±7.5	6.0
2	560	±7.5	8.4
3	730	±7.5	11
4	960	±7.5	14
5	1.3k	±7.5	20
6	1.7k	±7.5	25
7	2.3k	±7.5	35
8	3.0k	±7.5	45
9	3.9k	±7.5	59
10	5.4k	±7.5	81
11	7.35k	±7.5	110
12	10.5k	±7.5	160
13	14.5k	±7.5	220
14	22.0k	±7.5	330
15	30.0k	±7.5	450
16	40.0k	±7.5	600
17	52.5k	±7.5	790
18	70.0k	±7.5	1050

*Based on a deviation ratio of 5.

Figure 15. IRIG telemetry standards — subcarrier bands

Certain characteristics distinguish the digital computer requirements of an online data acquisition system from those of other computer applications. Of these, real-time processing capability is one of the most important. The system must be able to accept, and make decisions on, data as the data is being generated in the real world. System design, therefore, must take into consideration the interval between events, the maximum system response time (the elapsed time between the occurrence of an event and the system decision or action requirement based on that event), and the system data rates.

Some important computer characteristics required in online data acquisition systems are:

- Overlapped input/output and processing. —The central processing unit (CPU) must be capable of increased operating efficiency by overlapping input/output channel functions with processing. Real-time systems must provide overlapping of these functions so that the online devices may be serviced concurrently with the routine computation tasks required for the input data received from the devices themselves (that is, conversion of input data to engineering units or high-low limit check of the data for detection of out-of-tolerance conditions). A consideration in determining the amount of overlapping that may be implemented in a real-time data acquisition system is the interference characteristics of the input/output channels. Since both the CPU and the channels require storage cycles for references from main core storage and since only one access from storage can be made in every cycle, the CPU and the channels must time-share the main storage. It is this contention for storage cycles that is termed interference. If either the channels or the CPU were to receive every storage cycle, the other would be in a "lockout" condition.

- Input/output interrupt. —The computer must have the ability to interrupt or trap the main program and service an interrupt upon demand (for example, a contact sense interrupt indicating an alarm condition). The interrupt system must store the present CPU status, identify the type of interrupt, select and transfer control to the interrupt processing subroutine, and then subsequently restore the CPU to its original status.

- Indexing. —This feature enables the address portion of an instruction to be modified by adding or subtracting variable quantities contained in one or more special registers known as index registers. Indexing greatly simplifies programming of iterative calculations and reduces the number of instructions required, thus making available more core storage for data and further improving the program operating efficiency.

- Indirect addressing. —Indirect addressing is another technique used for improving program operating efficiency by address modification. A program instruction need only refer to a storage location containing another (indirect) address, which in turn directs the program to the needed data, system component or control function. For an example of the use of indirect addressing, assume that a number of program instructions must refer to a value which changes with each program iteration. Without indirect addressing, a number of modification instructions are required. With indirect addressing, however, the instructions can be indirectly addressed to one core storage location containing the value used by the program.
- Asynchronous input/output channels. —In many data acquisition systems there is a requirement for transfer of information both into and out of the CPU simultaneously to prevent the loss of data. An example of this is where the CPU may be generating "front end" analog channel addresses at the same time that analog data in digitized form is coming back to the CPU from the previously addressed analog channel. Also concurrent with this operation, there may be display, plotter, contact operate and/or contact sense operations. Asynchronous input/output channel capabilities permit the CPU to control these operations in a real-time environment.

- Internal speed. —Consideration must be given to the storage cycle time, the internal data transfer rate and the arithmetic speed of the CPU where the system computation requirements must be overlapped with high-speed data acquisition functions. For example, to acquire an analog sample, each analog channel must be addressed, the sample converted and transferred to the CPU, limit-checked, and logged on magnetic tape. The CPU time consumed in performing these operations must not exceed the interval between samples based on the front end sampling rate.

- Core Storage. —Some considerations to be made when determining the CPU core storage capacity required in a data acquisition system are (1) the amount of storage needed to handle the data samples, (2) the storage necessary for permanent CPU residence of the real-time control program and the various interrupt or trap processing subroutines, and (3) the availability of bulk storage for operational programs (consideration should be given to the access time and the transfer rate).

• Modularity. —The design of the data acquisition system must be such to permit expansion of both the storage capacity and the input/output channel capabilities to accommodate system growth.

• Reliability and flexibility. —The nature of data acquisition system applications demands a very high degree of operational reliability as well as the flexibility to accept a variety of serial and parallel input and output data formats.

PROGRAMMING SYSTEMS

Certain types of programs must be available to satisfy the programming systems requirements of a digital computer used for data acquisition and checkout functions in an operating environment. These are:

- Real-time data-handling and control programs
- System diagnostic and checkout programs
- Utility programs

Real-Time Data-Handling and Control Programs

A typical operating sequence of the data-handling and control subroutines in a data acquisition system consist of the following:

1. Initialization. —The programs are initialized by a loader subroutine which reads into the CPU such parameters as identification of the transducers to be sampled, sampling notes and limits to be checked. These initialized programs are then recorded on magnetic tape for later use.

2. Pretest. —A pretest calibration run is used to establish the reference measurement dimensions for the forthcoming test run.

3. Test Program. —The test program performs the actual computer tasks during a test and comprises the real-time monitor, the trap processor and the ordinary processing routines (contact sense acquisition and record, data acquisition and record from transducers, display, and other computation routines such as conversion to engineering units). The real-time monitor selects the routine to be executed. The trap processor decodes the interrupts and activates the appropriate routine for processing. (See Figure 16.)

4. Post-test. —A post-test calibration run is used to check for any drift from the original calibration reference dimensions established at the start of the test.

Real-Time Monitor

The principal means of controlling the selection and sequencing of the data-handling and control subroutines in a data acquisition system is a real-time control

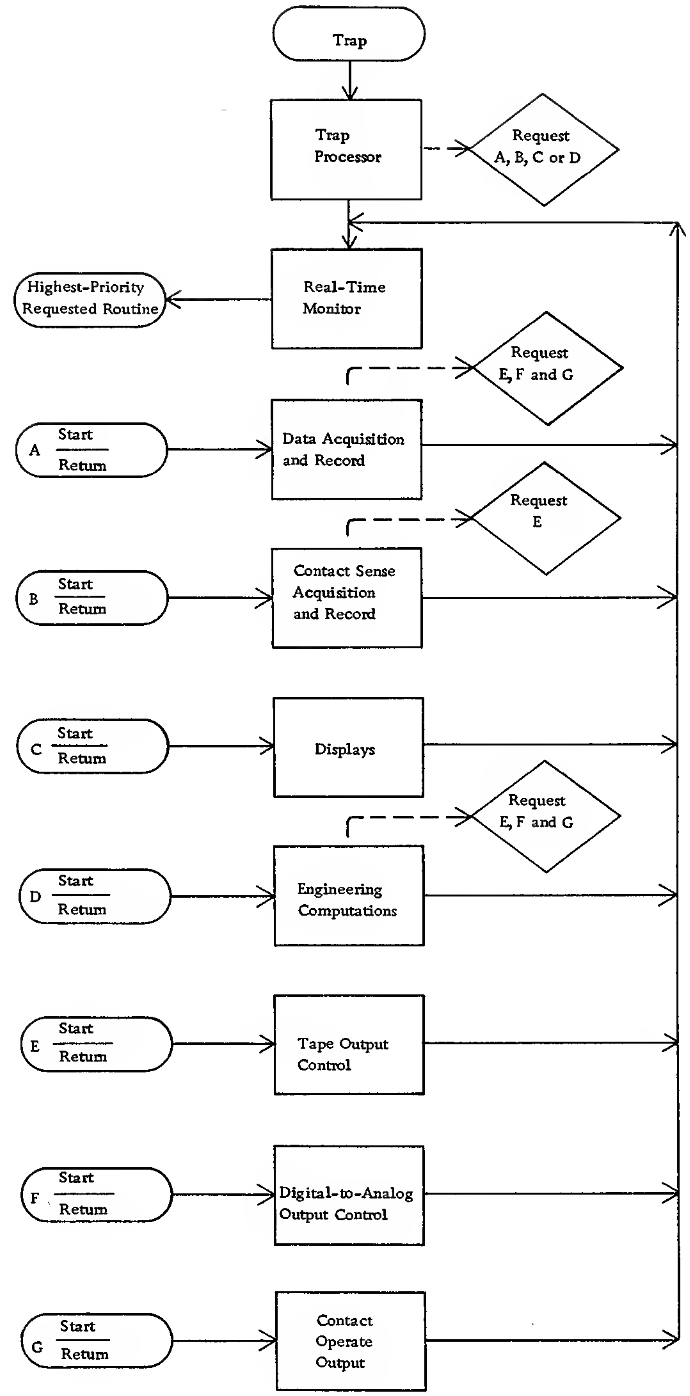


Figure 16. Data handling and control program organization

program (monitor). The functions of a real-time monitor are to (1) evaluate incoming data to establish relative importance and validity, (2) designate the subordinate operational programs to which the incoming data is routed, (3) interpret the processed results and dynamically alter the order of subsequent processing, (4) distribute the processed data to the output channels, and (5) present the status of the computations by means of output messages and displays.

Data acquisition system real-time requirements and the changing nature of physical systems are such that the sequence of control within the real-time monitor is not predetermined, but is subject to change in response to the occurrence of events of varying priorities within pre-established time schedules. The monitor provides system control and monitors the processing of interrupts or traps and controls the use of the ordinary processing routines necessary to perform the computation tasks. After the processing of each ordinary routine or after each interrupt is processed, the monitor program selects for processing the routine with the highest priority. Queues are used for stacking requests and storage as appropriate for each routine. If the selected routine was previously being processed and already interrupted, the CPU is restored to its interrupted status and control returned to the point of interruption.

Each processing routine entered generally contains a prefix or special program section which sets various flag bits in storage necessary for real-time monitor control. At the completion of a routine, control is returned to the monitor for selection of the next processing routine. At that time a unique suffix is entered into the routine program to turn off the in-process flags and, if required, request the next routine(s). This feature also makes it possible to change the priority of certain routines during the course of their execution.

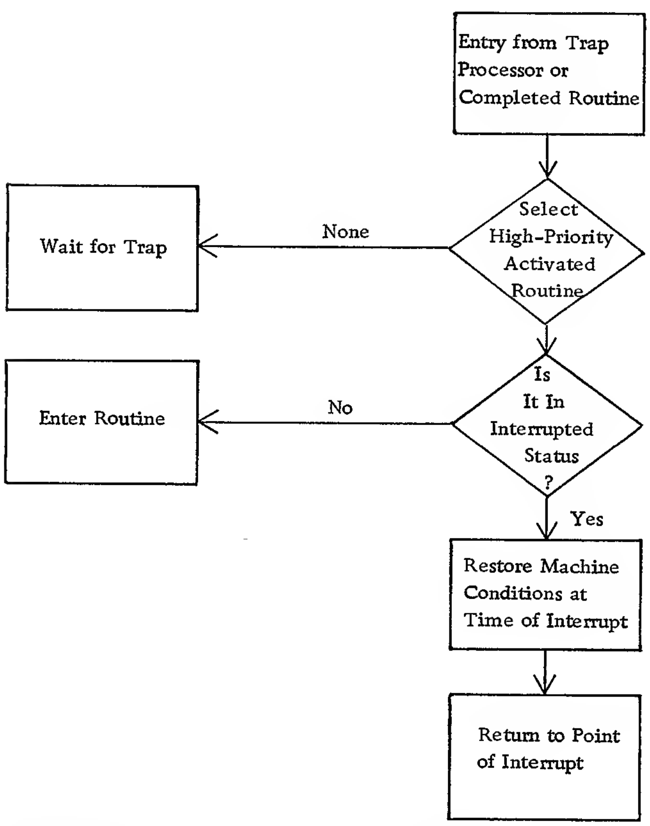


Figure 17. Real-time control program logic diagram

Trap (Interrupt) Processor

The trap processor provides for the CPU to be automatically interrupted and control transferred to fixed locations in core storage upon receipt of certain types of input or output signals. A status word which indicates the source and type of interrupt is also placed in core storage at the time the trap occurs. The format of this word is such that it can be rapidly decoded by the real-time monitor to initiate the required interrupt processing subroutine. The following table identifies some typical interrupts which may be encountered in a data acquisition system:

INTERRUPTS	
Type	Cause
External	Contact sense occurrence.
External	Events occurrence.
External	Initiate data acquisition.
External	Initiate display.
External	Parity error on data would reread.
Real-Time Data Channel End of Block	Normal completion of reading a complete data record
Data Channel	Normal completion of channel Input/Output commands for subsystems attached to a channel.
Data Channel Error	Error condition sensed by channel.

Input/Output Control

The input/output control function of the monitor program is to service input/output requests and establish CPU queues and priorities for these requests. When service is required by an online unit, the CPU is interrupted and a START I/O instruction is issued to the channel. This instruction specifies which channel and device are involved, and sets up a storage protection register (to ensure that input data is not inadvertantly read into this or any other program storage area). The input/output instruction also specifies to the channel where in core storage its program is located. After the input/output instruction has been executed, the CPU is freed and the channel program runs independently of the computational programs on a cycle-stealing basis. When the channel has completed its program (or encountered an error condition), it interrupts the CPU for a new command instruction.

System Diagnostic and Checkout Programs

Diagnostic programs are required to logically test the entire system in order to isolate malfunctioning components. These programs may be selected and initiated either manually or automatically upon detection of an out-of-specification condition. In many systems, diagnostic programs not only detect failures but in certain situations may also diagnose causes.

Data acquisition system diagnostic programs are divided between computer diagnostics and integrated system diagnostic programs. The computer diagnostics test the operation of the input/output channels and their trapping (interrupt) features along with the following components:

1. Central processing unit (CPU)
2. Card readers, punches and printers
3. Magnetic tape units
4. Core storage

To provide further assurance that the entire system complex is operational and to aid in preventive maintenance, integrated system diagnostic programs are provided. These programs simulate the operation of the real-time programs. To accomplish this, controlled inputs are inserted at points in the system, and calculated results are compared with expected values. Portions of the data and/or fixed data patterns are transmitted to allow the use of subsets to isolate specific malfunctions. The integrated system diagnostic programs should also include provision for testing each of the major system subsets including the following:

1. Data conversion subsystem
2. Digital-to-analog subsystem
3. Contact sense subsystem (sometimes called events subsystem)
4. Display subsystem
5. Contact operate subsystem (sometimes called control logic subsystem)

Utility Programs

Utility programs are used with data acquisition systems to facilitate development and operation of real-time and post-test application programs. The following are some of the more common types:

- Tape-to-printer/punch/typewriter — lists or punches cards from magnetic tape file records.
- Card-to-tape — reads punched cards to form a magnetic tape file.
- Storage and tape dump — lists from core storage or tape a printout of selected core storage locations and/or selected magnetic tape file records.
- Start program — provides necessary actions to initiate or restart job processing.
- Object card corrector — provides a "quick-fix" method for changing object program cards.
- Conversion processor — converts data formats under control of format information provided by print, type, card I/O and tape I/O utility programs.
- Print — generates either core storage output or magnetic tape output onto a printer in requested format.
- Type — generates either core storage output or magnetic tape output onto a typewriter in requested format.
- Card I/O — either reads or punches to or from core storage, or to or from magnetic tape files; processes all data formats converted by the conversion processor; provides an input reader for single instructions.
- Tape I/O — reads, writes, and positions magnetic tapes utilizing the channel features.
- Elementary functions — provides standard and accurate sets of sine, cosine, arc tangent, natural logarithm, exponential and square root function program instructions.
- Tape duplicator — generates a copy of selected magnetic tape files and records from one magnetic tape to another.

DATA OUTPUT EQUIPMENT

Data output equipment is required for three types of functions: data recording, data display, and operational control. High-speed data recording is usually done on digital magnetic tape. In small systems and in applications where little data recording is required, all data output recording may be performed on paper tape or punched cards, or by means of a printer.

Data display is required to inform the operator of the status and performance of a run so that he can make decisions for proper control. A number of different types of displays may be used.

Control equipment allows automatic control of the operation by the computer. The control may be a continuous or proportional type of feedback control, where the control action is a function of the difference between measured conditions and desired conditions; or it may be a discontinuous, switching type of control such as that used to change from one operating phase to another.

Types of equipment used for the above three functions include:

- Recording equipment
- Magnetic tapes
- Punched card equipment
- Paper tape equipment
- Printers
- Display equipment
    - Alphameric displays
    - X - Y plotters
- Strip chart recorders
- Cathode ray tube displays
- Status and warning lights
- Control equipment
    - Control relays or switches
    - Analog or proportional controllers

RECORDING EQUIPMENT

Magnetic Tape

Almost all data acquisition systems use magnetic tape for recording input data. Some systems record the analog data from the front-end equipment in computer-controlled data acquisition systems, raw input data is often recorded onto magnetic tape in digital gapped format. The central processing unit provides nothing more than a tape buffer and formatter in this type operation. The tape units must have writing speeds capable of accepting the incoming data at the rate received. Tape-writing speed is a function of tape speed and character density, and the block length or record size.

Two or more tape units may be necessary for long-duration runs to provide for rapid switching from one to the other when a tape reel is filled. Additional tape units are also usually necessary for program storage and for recording special data such as the results of calculations and conversions performed during the run. This capability may be provided alternatively by other storage devices such as magnetic disks, punched cards, paper tape or other devices.

Punched Card Equipment

Punched card equipment is frequently used in data acquisition systems to provide a convenient way to enter application programs and special control instructions into the computer. Punch and read speeds are generally not critical except in card-only systems where all recording is done on cards.

Paper Tape Equipment

Paper tape provides a low-cost storage medium for both data and programs. Many small, low-cost systems use paper tape for storage. Paper tape compatibility is also often required in larger systems at installations which have paper tape equipment presently installed.

Printers

Printers can perform a dual role of output recording and display. The results of calculations and conversions may be recorded on the printer and are available to the operator during operation. In addition to printing alphameric characters, the printer may be used as a plotter in applications where plotting speed is not a critical factor.

The printer performs an extremely important role in system checkout and the diagnosis of troubles. As a very flexible alphameric display, the printer can indicate the status of the central processing unit and all peripheral equipment as checkout is performed. With switchable diagnostic programs it can print out diagnoses of failures in the system.

Printing capability in data acquisition systems may be provided by conventional high-speed line printers, if speed is a factor, or it may be provided more inexpensively by output typewriters.

DISPLAY EQUIPMENT

Alphameric Displays

One form of visual alphameric display used for "quick look" shows output data directly in decimal

form — typically as three or four digits with sign. Additional digits or alphabetic characters may show identification data such as channel number. Some of these displays may have other features such as decimal point with position control as part of output data, limit indicators which show whether data is in or out of predetermined limits, and manual selection switches for selecting the channel to be displayed.

Several types of alphameric displays are commercially available. Mechanical displays use motor-driven character wheels or characters positioned by solenoids in response to input data. Another common type of electronic display uses electrode switching in a glow discharge tube to switch characters. These are inexpensive, fast and reliable. Back- or edge-lighted displays rely on the switching of lights which illuminate separate characters in order to change the display. Other displays form characters by illuminating combinations of line segments.

The simplest types of decimal displays accept data from the central processing unit in ten-line decimal form. Displays with built-in decoders may be obtained which accept binary or BCD data. In many cases, the driving of output displays by the computer may require binary-to-BCD or binary-to-decimal output conversion.

If a number of remotely located displays are required for displaying a number of different parameters or channels of information, it is often practical to provide addressable displays. All display data is sent out on a single data bus along with an address of the display unit for which it is intended. A comparator at each display examines each address and compares it with the address for its display. If a correlation is found, the associated data is gated into the display unit.

X - Y Plotters

X - Y plotters draw graphs of two variables (dependent and independent) from the analog data. They may be used to plot a computed parameter versus a measured parameter (for example, engine thrust versus combustion chamber pressure) or they may plot a computed parameter versus time. Some X - Y plotters have self-contained digital-to-analog circuitry and may accept digital data directly from the computer.

Strip Chart Recorders

Strip chart recorders record output data in analog form by means of a moving pen on a motor-driven paper chart. Resolution of the recording is typically of the order of one or two percent. Because the movement of the pen is slow, the frequency response of these devices is low. Recorders are commercially available which are capable of reproducing frequency components from about one cycle per second maximum up to several hundred cps. Only a relatively few data channels can be practically handled with strip chart recorders, since each channel being recorded requires a separate pen.

Strip chart recorders are often used in computer-controlled data acquisition systems to record and display calculated or converted operating parameters in easily readable form. The fact that a permanent record of the displayed data is available after the operation is complete is often advantageous. Strip chart recorders may also be used in a postoperation mode for a quick-look analog plot of selected channels of data previously recorded on magnetic tape.

Since strip chart recorders require analog input voltages, they must be driven from the central processing unit through digital-to-analog converters. The digital-to-analog converter may be incorporated into central processing unit output subchannels or they may be separate units. The restricted resolution of the strip chart recorders requires digital-to-analog converter resolution of six to eight bits only. This allows the computer output word to be composed so that it can drive two or more digital-to-analog converters simultaneously.

The rate at which the central processing unit must send new data to (that is, update) the strip chart display is dependent upon the frequency components which must be reproduced on the chart. Data rates for strip chart recorders in typical systems are ten to 25 words per second per recorder. The data rate must be several times higher than the highest frequency component to be reproduced.

Some recorders employ photo-optical techniques to achieve a higher-frequency response. They have low-inertia moving coil elements with associated mirrors to deflect light beams. Recording is done by the light beams on sensitized paper charts. Frequencies in the input data up to several thousand per second can be reproduced.

These recorders are driven from the central processing unit through fast digital-to-analog converters. Because their frequency capability requires a high data transfer rate from the computer, they are generally used to record only a few channels of data or small increments of data.

Cathode Ray Tube Displays

The simplest type of cathode ray tube display is an oscilloscope with X and Y deflection amplifiers driven from the central processing unit through digital-to-analog converters. By suitable programming, the display can be made to plot curves and generate special patterns. A third digital-to-analog

converter may also be used to provide Z axis (intensity) modulation of the beam for emphasizing scale markings or parts of the display.

Since the resolution of common oscilloscope displays need not be much more than about one percent of full scale, seven- or eight-bit digital-to-analog converters are usually adequate for the X and Y axis outputs. A suitable oscilloscope display output can thus be provided by breaking a 16-bit output data word into two seven-bit X and Y deflection words and a two-bit Z axis modulation word. A single 16-bit transfer through three digital-to-analog converters can thus be used to set the position and intensity of the oscilloscope trace.

More sophisticated cathode ray tube displays are obtainable with higher resolution and greater display capability. Resolutions up to one part in 4,000 can be obtained with tube face diameters of ten inches or more. Character generation capability can also be provided by special character function generators in either the CRT display itself or by programming. Storage capability for holding and regenerating displays can be provided with digital storage or with cathode storage tubes.

A further capability may be provided for expanding or contracting display scales, for magnifying portions of a waveform, for erasing or for changing a display manually.

A useful type of cathode ray tube display for systems having a large number of analog input channels is the bar chart display. This depicts all input channels as bars on a single representation where the length of the bar represents the value of the channel input voltage. Every tenth bar may be intensified to facilitate channel identification. In this mode it is useful in setting up, checking out and diagnosing troubles in a multichannel data acquisition system, since it shows total operation at a glance. Malfunctioning channels may be identified quickly.

Cathode ray tube displays are available which accept sequential eight-bit digital data words (corresponding to channel inputs) and to generate the bar displays.

Status Indicators and Warning Lights

Status lights are important in data acquisition systems to display the state of valves and switches and/or the occurrence of events. Warning lights may be used to signal the occurrence of out-of-limit or dangerous data values, or the failure of some action to take place in proper sequence or when commanded. Status lights inform the operator of the present status of an operation, whereas warning lights direct an operator to take some action to avert a dangerous or erroneous condition.

Status and warning lights are actuated by control relays or latching switches which are addressed from the central processing unit. Banks of relays or latching switches containing an address decoder are connected to a low-speed data channel. Each relay or switch is then actuated by a unique address.

CONTROL EQUIPMENT

Two types of control equipment may be required in any data acquisition system application: control relays or switches, and analog or proportional controllers.

Control Relays or Switches

Control relays or switches are used for such things as sequencing of actions or phases, applying various excitations for calibration or checkout purposes, and step control of operating parameters. An example of the use of control relays is the sequencing of the various valve closures and switches required for the countdown phase of a rocket engine test.

Control relays are generally actuated by decoding an address from the central processing unit. For latching relays, sufficient addressing capability is required to establish either an open or a closed condition on any relay. A separate address is usually provided to reset all relays to an open condition.

Analog or Proportional Controllers

Analog or proportional control capability is required where a smooth continuous control of an element or mechanism is required. An operation of this type is the requirement to control a position servo and to exercise it through its range during a run. A rocket engine, for example, will have its nozzle rotated through a range of gimbal angles during checkout.

Analog outputs for this type of control are obtained by using digital-to-analog converters to convert central processing unit output words to analog form. The computer flexibility, then, may be used to generate a wide range of output functions for control purposes. Special analog drivers may be needed to provide the power levels required to drive servos.

CONCLUSION

In the design of a data acquisition system for either an offline, data logging or online, real-time operating environment, certain aspects of the application specifications must be considered. These include:

- Output signal levels from the transducers
- Signal conditioning requirements
- Blocking of transducer output signals
- Required sampling rates
- Resolution and accuracy requirements
- System interrupt requirements
- Distance between front-end components
- Input/Output interface rate requirements
- Central processing unit capabilities
- Programming system requirements
- Quick-look requirements
- Operating environment

Definition of these application specifications guides the systems engineer or designer in the selection of the necessary components for a configuration which will satisfy all of the system requirements.

This manual has presented a general discussion of the characteristics of the components or functions found in many types of data acquisition systems. The engineering considerations for each component or function must be examined in detail by the system designer in the development of an operating system.

GLOSSARY

Accuracy. —A number or quantity which defines the limit of error.

Accuracy rating. —The limit which errors will not exceed when the device is used within the limits of rated operating conditions.

(a) For instruments with uniform scales, accuracy rating is generally expressed in percentage of scale span, or as a fixed value in units of the measured quantity. In most instances, percentage of scale span is preferred.

(b) For instruments with nonuniform scales, accuracy rating is generally expressed in percentage of scale length.

Amplifier. —The device required in a high-speed data acquisition system to change the millivolt signal to a level which can be multiplexed at high speeds without introducing appreciable error. Differential amplifiers are most common in DAS for balanced (double-ended) inputs.

Bar graph. —A cathode ray tube display which allows more than one input signal to be displayed simultaneously on its face.

Calibrated accuracy. —A number or quantity which defines the maximum error throughout the scale under "standard" test conditions of temperature, humidity, barometric pressure, etc.

Calibration data. —Calibration curve data on all individual instruments which are generally fed into the computer prior to the test run (generally stored on cards which can be updated easily).

Closed-loop system. —A system which not only receives analog inputs but also produces analog, digital or binary (on-off) outputs to control a process, test, etc.

Conversion speed. —The rate of analog-to-digital conversion. It should coincide with multiplexing speed.

Data dump. —The bringing in of data from a buffer, core, etc., to the computer or the writing of all test data (raw, edited, etc.), as desired, onto a recording medium (magnetic tape, cards).

Dead band. —The range through which the measured quantity can be varied without initiating response. Transducers, amplifiers and recording devices all exhibit this phenomenon.

Dead band rating. —The limit which the dead band will not exceed under rated operating conditions.

Display units. —Visual records of a permanent type (ink recorder) or nonpermanent type (cathode ray tube). These devices receive digital values in a continuous manner from the computer and produce visual approximations of them. The CRT must be frequently "updated" or regenerated, because it is a continuously fading record.

Drift. —A gradual change with time in the relationship of output to input. Expressed as the maximum change in percentage of span during a specified time. Long-range and short-range drift figures should be stated.

Encoder. —A mechanically positioned device which converts angular rotation into a proportional digital value through brush contacts or optical methods.

Error. —The difference between the indication and the true value of the quantity being measured. A positive error denotes that the indication is greater than the true value. Generally stated as $\pm$ of a full-scale instrument's output.

Excitation voltage. —The power supplied to an instrument (such as a strain gage) to obtain variations in potential.

Fixed data. —Sometimes called manually entered data or housekeeping data. It generally includes such information as:

Test run number
Date
Computations required
Operator
Run duration
Serial number of model under test
Data dump format
Fuel or material unique to test

Such information is recorded onto the magnetic tape record prior to every run.

Formatter. —A device including buffers and controls to record data on magnetic tape in a gapped form.

Frame. —A block of data consisting of time, the digital value of the scanned inputs (generally all) and their signs, plus an end-of-record mark. (Several frames of data may also be called a "block".)

Frequency counter. —A device to convert pulses, sine wave signals, and time-elapsed events into a summed value utilizing a given time increment. Such devices start and stop counting under computer control. They are used to measure flow, cycles per seconds, etc.

Full scale. —The value, in scale units, representing the upper end of the range.

Gapless tape. —A magnetic tape upon which raw data is recorded in a continuous manner — that is, the data is "streamed" onto tape without the word gaps. The data still may contain signs and end-of-record marks in the gapless form.

Gapped tape. —A magnetic tape upon which blocked data has been recorded. It contains all the flag bits and format to be read directly into a computer for immediate use.

High-level outputs. —Transducer outputs in the range of one to ten volts.

Hybrid computer. —A system composed of a general-purpose digital computer, an analog computer, and the linkage equipment for communication between them — plus the necessary interfaces and signal conversion devices.

Hysteresis. —That property of an element evidenced by the dependence of the value of the output, for each value of the input, upon both the prior history and the most recent direction of change in the casual input. The hysteresis curve of an instrument system must be considered repetitive.

Hysteresis error. —The maximum separation, due to hysteresis, between upscale-going and downscale-going indications of the measured variable during a full-range traverse, after transients have decayed. This is considered to be a factor of an instrument's linearity or nonlinearity.

Input impedance. —The impedance from the input terminal through the amplifier into the analog-to-digital converter, with the multiplexor switched to a given input; generally high impedance in excess of 100 megohms.

Interface. —The adapter attached to the computer for the direct and controlled entry of digital data (from an analog-to-digital converter, for example).

Interrupt or trap. —The capability of an online computer to stop a main program by an external signal and, through an executive program, direct itself to an appropriate interrupt subroutine and subsequently return to the main program.

Limit of error. —The maximum error throughout the scale under specified conditions.

Linearity. —The closeness with which the curve of output approaches the curve of the input. Usually expressed as a nonlinearity, the maximum deviation in percentage of span for any point within the range, or a percentage of the usable output signal.

Low-level outputs. —Transducer outputs in the range of $\pm$ 10 mv to $\pm$ 500 mv.

Measurand. —A physical quantity, property, or condition which is to be measured — electrical, physical or optical (light).

Measured quantity. —The variable or parameter which is applied as input and is the equivalent of the measurand.

Mercury-wetted relay. —The switching devices in a low- or medium-speed multiplexor.

Open-loop system. —A system which receives analog, digital or binary (contact sense) intelligence inputs. No control function is accomplished.

Patch board. —A manually wired board to provide for input-selection and input-recording sequences in data acquisition systems.

Performance rating. —The limits of the values of specified performance and functional characteristics which will not be exceeded under any combination of rated operating conditions. The number of repetitive operations must be stated.

Plotter. —A display device which can generally plot an X value against a Y value. Plotters are either of the discrete point (of sensitivity) or the continuous-line type. (The former are preferred in digital data acquisition systems.)

Quick look. —A mode of operation in which sampled raw input data is manipulated by the computer and displayed (on either a display unit or a high-speed printer), so that the operator can observe completed performance data in some meaningful form. It is dependent upon the computer used and the ADC rate. Incoming data may have to be halted during the execution of the quick look subroutine.

Range. —The region covered by the span, expressed by stating the two end-scale values. If the span

passes through zero, the range is stated by inserting "0" between the end-scale values. (If so, it may also be considered bipolar or zero-offset in nature.)

Rated operating conditions. —The limits of specified variable or conditions to which the system or device may normally be exposed and under which normal satisfactory performance may be expected.

Readability. —The smallest indication, expressed in percentage of usable signal output, which can be read with ease by estimation of fractions of the smallest scale division.

Real-time clock. —Generally a relative time base in the system which allows time to be recorded with each frame of data.

Reproducibility. —The ability to consistently repeat a value of output for the same input under identical conditions of operation at different times. To be of value a time limit must be stated to take drift into consideration.

Resolution. —The maximum capability of a system to convert an analog signal (0-50 mv, for instance) to a proportional digital value (generally equivalent to 5,000 or 9,999, the quantized value).

Scale length. —The chart or scale width traveled by the pen or indicating pointer in traveling from one end of the scale to the other.

Scale span. —The span expressed in scale units. An indication of the least readable increment is also generally stated.

Sensitivity. —Of discrete reading devices such as analog-to-digital converters or pulse counters, the least interval in space, time or quantity between adjacent readings with varied but minimum input values.

Shielding. —The practice of electrically isolating instrument inputs to a data acquisition system through the enclosure of signal wires in metallic sheathing or conduit properly grounded.

Signal leakage. —The effects of loss in signal strength due to the ineffectiveness of dielectric materials in the system's terminal/multiplexing unit.

Signal noise. —Spurious and random electrical voltage/current imposed on the signal input lines from sources other than the data system.

Source impedance (output impedance). —The impedance of the input signal looking from multiplexor terminal toward the instrument; generally low (less than 1,000 ohms).

Span. —The algebraic difference between the end-scale values.

Standard deviation. —A value equal to the root mean square (RMS) value of all individual deviations from the arithmetic mean value.

Steady-state data. —Data taken when an instrument is at a given power setting. A state of equilibrium exists.

Suppressed zero range. —A range which does not include zero. A segment of the instrument sets output.

Suppression ratio. —The ratio of the smaller end-scale value to the span, both values being in units of the measured quantity.

System grounding. —The systematic location of system grounds for the "front end", computer and instrument measurement sets.

Telemetry inputs. —System inputs from remotely located radio communication-oriented systems. The various telemetry systems can be either:

FM - Frequency Modulation
PAM - Pulse Amplitude Modulation
PDM - Pulse Duration Modulation
PCM - Pulse Code Modulation

Transducer. —A device which converts an incoming transmitted signal from one medium or range of values to a proportional outgoing transmitted signal in a different medium or range of values. Synonymous with pickup, detector, sensing element, power relay, etc.

Transients or dynamic data. —Data taken before, during and after a step function change in operating level.

Transmitted signal. —An output signal from a device, standardized as to range and proportional to a measured quantity, which may be used an an input to a receiving device at a remote location.

Transmitter. —An instrument or device which converts an input in the form of a measured quantity to an output in the form of a transmitted signal.

Zero shift. —A change in output at zero input. Expressed as percentage of span and differentiated from zero drift by occurring quickly rather than over an extended period.

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